Why quantum mechanics?

- Quantum mechanics is essential to all fields of physics and many engineering fields (e.g., semiconductors and nanotechnology)
- The twentieth-century view of the universe necessitated by quantum mechanics is something non-physicists should know as well
- People are fascinated by modern physics concepts (e.g. *A Brief History of Time* or *The Elegant Universe*)
  - No one sells books about torque
Current events

- AP Physics B contains 10% atomic and nuclear structure – which means it has less quantum mechanics than AP Chemistry (20%)
- Serway’s book spends about a sixth of the book on modern physics (often skipped, since it is at the end)
- NGSS has one relevant standard:
  - HS-PS4-3: Evaluate the claims, evidence, and reasoning behind the idea that electromagnetic radiation can be described either by a wave model or a particle model, and that for some situations one model is more useful than the other.
Lessons from IMSA

- Modern Physics offered as a one-semester class (with lots of quantum mechanics included)
- When the difficulty increased, enrollment also increased
- Students responded strongly:
  - “I had my mind blown every class”
  - “This is the most interesting class I’ve ever taken”
  - “ModPhys was the highlight of my day”
  - “Before this semester, I hated physics, but now, that hate has subsided and I actually find myself interested enough to pay attention, take notes, do my homework, and look up other resources in my free time.”
- Two students said they decided to become physics majors because of this class
Quantum Mechanics

- Quantized energy levels of atoms in the Bohr model are the most applicable part of quantum mechanics, but:
  - They aren’t that exciting
  - Chemistry already does that part
- Many students love the weirdness of quantum mechanics
- The most interesting part of quantum mechanics is not uncertainty
  - People are used to being unsure
  - We are not used to our observations changing the behavior of the universe
The standard curriculum

(From Serway/Faughn, 7th edition)

- Blackbody radiation
- The photoelectric effect
- X-rays
- X-ray diffraction
- The Compton effect
- Wave-particle duality
- The wavefunction
- Heisenberg’s uncertainty principle
- Scanning-tunneling electron microscopes
- The Bohr model
- The hydrogen atom
- Spin
- Semiconductors

- Requires advanced thermodynamics
- Requires circuits
- Nothing to do with quantum mechanics
- Hard to explain
- Not useful for deeper understanding
- Poorly explained
- Covered by AP Chemistry
- The important part!
- The important part!
- The important part!
Proposal

- Why go in chronological order? We don’t teach any other physics that way
- Skip the boring stuff – kids don’t get it anyway
- Jump right into the interesting stuff:
  - The wavefunction and measurement
  - Compatible and incompatible observables
- Focus on the easiest QM systems:
  - The double-slit
  - Spin
- For students who like to talk about such things, spend some time on the philosophy
The double slit

- This example best explains the mechanism of quantum mechanics
  - Show that light is a wave with an interference pattern (lab)
  - Mention (or show, if you want) that Einstein found light is a particle
  - Ask: what happens if you shoot only one particle at a time at slits?
  - Show YouTube video of actual experiment
  - Discuss why this is weird
  - Add sensors to see which slit the particle passed through – show how interference disappears

- See attached talk at the end of this presentation
The fundamental difference of quantum mechanics is that you cannot write any expression such as $x = 3 \text{ m}$.

You can only give probabilities of being at a particular place.

The probabilities are represented by an (unobservable) wavefunction.

The strangest part – when we make a measurement, the wavefunction collapses to the value we measured, thus changing its behavior.

Our observation affects the behavior of the universe!
Classes who enjoy discussions can spend a long time on big questions:

- How can our observation affect reality?
- What is a measurement?
- Is the universe fundamentally probabilistic?
- Is consciousness necessary to induce a measurement?

And, if you dare:

- What implications does a probabilistic universe have for free will?
- Is consciousness just a series of random quantum measurements that give the semblance of purpose?
- Is it easier or harder to reconcile quantum mechanics with an intervening God?
More advanced topics

- For those with the time and inclination, there is much more quantum mechanics that can be explored without any fancy mathematics.
Incompatible observables

- The center of the weirdness of quantum mechanics
- Measurements of two incompatible observables are mutually inconsistent – knowledge of one invalidates knowledge of the other.
- For example, if you measure the $x$ spin of a particle, then measure the $y$ spin, then measure the $x$ spin again, you may get a different answer
- Position and momentum are incompatible observables – hence, the Heisenberg uncertainty principle
A fundamental result of quantum mechanics – nothing to do with experimental error

There is a limit to how sure we can be of position and momentum *simultaneously*

You can measure position as well as you want, and then measure momentum as well as you want

However, if you then measure position again, it will likely be different from what you measured before
Spin

- A good illustration of incompatible observables
- A fundamental, quantized amount of angular momentum intrinsic to all particles
- Simplest example: spin-$\frac{1}{2}$
  - When you measure spin along a certain axis, it can only be up or down – nothing else
- Spin along one axis cannot be known at the same time as spin along any other axis
  - Suppose you measure z spin to be spin up
  - Then you measure y spin to be spin up
  - If you measure z spin again, you might get spin down instead of spin up (50% chance)
  - Measuring a spin “resets” the spins in the other directions
Stern-Gerlach devices

- One way (from Feynman) to discuss quantum mechanical principles is through Stern-Gerlach devices – devices which measure spin.
- Thus, SG-z means that you measure the spin in the z direction.
- As you can see, in this case you would have no particles coming out.
Stern-Gerlach devices

- However, a measurement of x spin, which does not commute with z spin, makes the previous measurement no longer valid.
- Thus, our measurement changes the outcome.
Many students enjoy working out larger, more complex Stern-Gerlach networks. These aren’t too applicable to physics, but they can be fun.
What is quantum mechanics?

- The good news: Quantum mechanics is the only theory we have that explains our experiments
- The bad news: Quantum mechanics makes no sense
The double-slit experiment

- Suppose we shoot particles through two slits at a screen on the other side
- The particles will collect in two rows on the screen
- So far, so good
The double-slit experiment

- Suppose we do the same thing with waves (e.g. water waves)
- Now waves from the two slits interfere with each other
- Get a series of light and dark rows on the screen
Is light a particle or a wave?

Thomas Young showed in 1801 that light has a double-slit interference pattern like a wave.

Albert Einstein showed in 1905 that light had to be composed of particles (photons).
The weird part

- What if we shot only one photon at a time through the slits?
- Should be impossible to interfere – should get two rows on the screen
- Here is a video of a real experiment.
Huh?

- Even though only one particle goes through the slits at one time, we still see interference!
- A photon interferes with itself?
- Each photon goes through both slits?
Trying to understand

- Okay, a photon can only go through one slit or the other
- Put sensors in to figure out which slit it went through
The even weirder part

- The sensors do their job: the photon shows up in only one slit or the other…
- But the interference pattern disappears!
This means that our measurement changes the result of our experiment!
The Copenhagen interpretation

- A particle is actually not at a particular position; it has a wavefunction that gives a probability of being at a position.
- When we make a measurement, we measure only one position, chosen at random.
Wave-particle duality

- This means that:
  - Particles actually behave as waves
  - But we measure them as particles

- Or, if you prefer:
  - Particles propagate as waves but interact as particles

- Or, more simply:
  - Particles act like waves when we aren’t looking
What this means

- A measurement is a fundamentally different physical process
  - No mathematical representation
  - The only truly random process
  - The only truly irreversible process

- What is a measurement, anyway?
  - The interaction of a microscopic system with a macroscopic one?
  - The transfer of information?
  - The intrusion of human consciousness?
Measuring a measurement

- Can’t we do an experiment to find out more about what a measurement is?
- Not easily – an experiment needs a measurement, and we can’t take a measurement of a measurement
- We are asking about what happens before we measure it – can we ever know that? Does it even make sense to ask?
The end of science?

- Measurement is fundamental to the scientific method
- Thus, it’s not clear if science can tell us anything about measurement itself
- Quantum mechanics has at its heart the old question: if a tree falls in a forest…
- But who knows? We may figure something out